RESEARCH ARTICLE

Exercise Effects During Diving and Decompression on Postdive Venous Gas Emboli

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Background: Exercise and diving have generally been associated with an increased risk of decompression sickness (DCS), thus accounting for the lack of studies involving exercise during decompression. However, theoretical and observational evidence contrary to this association motivated the present investigation on the effects of moderate, intermittent exercise during diving and/or during decompression on venous gas emboli (VGE) activity following a dive. ***Hypothesis:*** VGE observed at both the precordium and subclavian vein sites after diving should be reduced if moderate exercise is performed during decompression vs. remaining inactive. ***Methods:*** In a water-filled hyperbaric chamber, 39 healthy male subjects were compressed to a pressure of 450 kPa (45 msw) for 30 min followed by 55 min of staged decompression. Subjects were either active or inactive at the bottom phase (450 kPa) and/or during the decompression. Activity comprised three 5-min intervals of moderate arm or leg exercise at the bottom and five such intervals during decompression. After decompression, VGE were monitored at the precordium and subclavian vein sites using Doppler detection. Bubble activity scores were converted to various indices and analyzed using non-parametric statistics. ***Results:*** VGE activity was invariant as to whether subjects were active or sedentary during the bottom phase of the dive. However, it was significantly lower for all indices examined ($p < 0.05$) after dives in which exercise was performed during decompression vs. inactive decompression. ***Conclusion:*** Moderate, intermittent physical activity during decompression decreases VGE activity after diving.

Keywords: bubbles, Doppler, diving, DCS, risk, physical activity, decompression.

EXERCISE IS INTRINSIC to military and commercial diving, and exercise has generally been associated with an increased risk of decompression sickness (DCS). Vann and Thalmann (29) summarized the research on this association in terms of the occurrence, intensity, and duration of exercise. Vigorous or ballistic exercise before diving, sufficient to cause muscular soreness, may produce microscopic muscular injuries, which could become the sites of bubble formation and subsequently increase the risk of DCS (7,28). Dervay et al. (6) also observed that the incidence of DCS increased when strenuous leg exercise was performed immediately before altitude decompression. During diving, the increased metabolism of exercise can enhance the rate of gas absorption, rapidly causing inert gas saturation of tissues and increasing the risk of DCS (10,14,28,29). After diving or decompression to altitude, strenuous muscular exertion such as weightlifting might induce changes in venous pressure and blood flow that produce Reynold's cavitation (13). Cavitation in supersaturated fluids produces gas nuclei (13) leading to bubble formation and a corresponding increase in the risk of DCS (11,27,29). Thus, strenuous exercise before, during, and/or after diving, for various reasons, has been associated with an increased risk of DCS (4).

Ample evidence, however, also supports the idea that moderate exercise during decompression facilitates inert gas elimination and reduces the risk of DCS in divers (15,22,23,28,29) and astronauts during oxygen prebreathe protocols before altitude decompression (17,30). This concept, which originated with Boycott et al. (1) in 1908, has recent theoretical support (11), provided that bubbles do not form prior to the commencement of exercise. Yet, exercise during decompression is still generally regarded as unsafe. A previous report (15) on a portion of the data presented herein compared active and inactive decompression protocols, and concluded that moderate intermittent exercise during decompression significantly reduced the amount of Doppler-detected asymptotic venous gas emboli (VGE) after diving. The purpose of the present investigation was to confirm this finding with additional analyses of the data and to compare these findings with the effects of moderate exercise during the bottom phase of the dive.

VGE data were used to determine the effects of exercise during decompression based on the following factors: 1) the knowledge that the formation of gas bubbles precede the symptoms of DCS (25); 2) an association between observable bubble activity and an increased incidence of DCS (20,25); 3) the convenience and analytical advantages of Doppler monitoring for VGE (20); and 4) the avoidance of the safety and ethical issues of intentionally inducing DCS to quantify its risk. The hypothesis of this investigation was that bubble activity observed at both the precordium and subclavian vein

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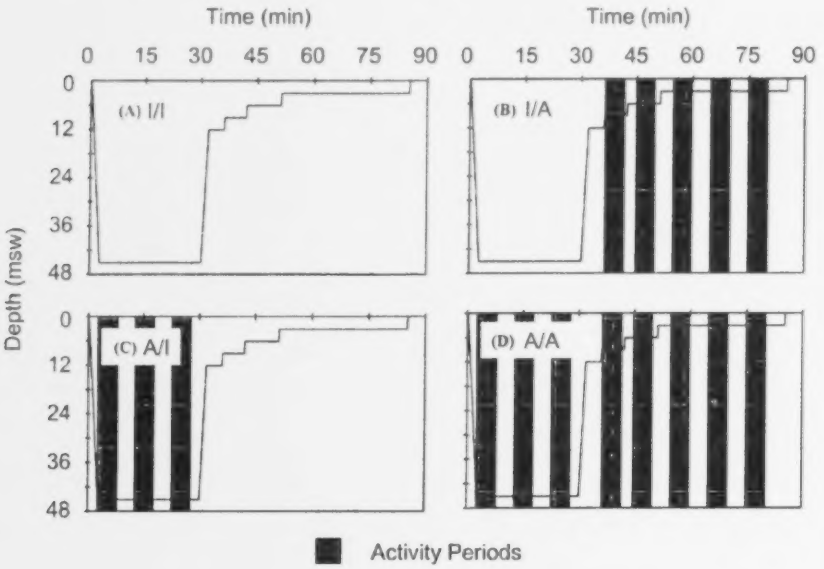

Fig. 1. Dive profile used (45 msw for 30 min) showing activity periods during the bottom and decompression phases of the dive: (A) Inactive/Inactive; (B) Inactive/Active; (C) Active/Inactive; and (D) Active/Active.

sites would be reduced if moderate exercise were performed intermittently during decompression after either moderately active or inactive dives.

METHODS

Experimental Protocol

The investigation was approved by the Human Research Ethics Committee of the Defense R&D Canada-Toronto (formerly DCIEM®) and conducted in the water-filled (8 ± 2°C) portion of the hyperbaric chamber. There were 39 healthy men (11 Canadian military divers and 28 commercial diving students) who signed written informed consent forms in accordance with the institution's human ethics policies and procedures. These subjects voluntarily performed a total of 85 simulated dives during the study. Each experimental dive (**Fig. 1**) was to a pressure of 450 kPa (45 msw) for 30 min followed by 55 min of staged decompression according to the DCIEM® Standard Air Diving Table (5). A minimum of 5 d without diving was imposed between the start of any two experimental dives. Subjects participated in one or more of nine trials depending on the type and time of exercise.

Active subjects performed 5 min of moderate arm or leg exercise beginning at minutes 5, 15, and 25 on the bottom, and/or minutes 7, 15, 25, 35, and 45 of the decompression (Fig. 1). Each exercise period was followed by 5 min sitting at rest on a cycle ergometer. Leg exercise was performed on a submersible, electrically braked cycle ergometer (Warren E. Collins, Braintree, MA) installed in the dive chamber and waterproofed in the manner described by Thalmann et al. (26). Arm exercise was performed on a customized paddle ergometer or by lifting weights (approximately 2 kg). The intensities of both the arm and leg exercises were maintained at heart rates that corresponded to approximately 50% of each subject's previously determined respective maximal rates of oxygen consumption (i.e., arm and leg $\dot{V}O_{2max}$; 12,23,24). Heart rate was monitored via an unorthodox precordial electrocardiograph lead obtained by using three chest electrodes hard-wired through the data acquisition system of the dive chamber and connected to standard clinical electrocardiograph recorders equipped with digital cardiotachometers (MultiCare Model 304, Rigel Research Ltd., Morden, Surrey, UK). No attempt was made to correct heart rates for the effects of immersion or increased P_{O_2}.

Bubble Monitoring and Evaluation

VGE monitoring was conducted at approximately 21, 61, 100, and 147 min following decompression using Doppler ultrasonic bubble detectors (TSI DBM 9008, Techno Scientific Inc., Woodbridge, Ontario, Canada). For some subjects with little or no observable VGE, monitoring was terminated after 100 min. Each subject's left and right subclavian and precordium veins were monitored as indicators of VGE activity in the upper and lower limbs, respectively, and assessed with the subject at rest and following a specific movement. Movement was a deep knee-bend for the precordium, and a clenching of the fist on the side being monitored for the subclavian veins. For the latter, the higher of the two shoulder signals was used to represent bubble activity. Experienced Doppler technicians manually categorized the auditory output from the bubble detector using the Kisman-Masurel (K-M) code (20).

The 3-digit K-M code (each digit ranging from 0 to 4) represents the frequency of bubbles (number of bubbles per cardiac cycle), the duration (percentage of cardiac cycles with bubbles at rest or the number of cardiac cycles with elevated bubble sounds after the specified movement), and the amplitude of the bubble signal relative to normal cardiac background sounds. The K-M codes were subsequently converted to a bubble grade

TABLE I. CORRESPONDENCE BETWEEN THE K-M BUBBLE GRADE (BG), THE NUMERICAL BUBBLE GRADE (d), THE BUBBLE COUNT ESTIMATE (BCE), AND THE BUBBLE SEVERITY ESTIMATE (BSE, RANGE SHOWN).

BG	0	I−	I	I+	II−	II	II+	III−	III	III+	IV−	IV
d	0	0.67	1	1.33	1.67	2	2.33	2.67	3	3.33	3.67	4
BCE	0	0.01	0.05	0.1	0.15	0.2	0.3	0.5	1	2	5	10
BSE	0	0.400–0.620	0.635–1.018	1.091–1.289	1.561–1.729	1.732–3.390	3.476–4.277	4.349–5.604	6.654–10.74	11.49–17.16	18.14–20.79	21.97–35.14

(BG) from 0 to IV based on a 12-point ordinal scale (I−, I, I+, II−, II, ... IV−, IV; 20).

The maximum observed BG is often used to represent the decompression stress of a dive. However, important temporal information can be lost by ignoring the many submaximal BG observations made on each subject following a dive. Thus, a number of methods were used to convert the K-M code and BG to other scores and indices, which facilitated a more comprehensive analyses of the data. The ordinal BG values were first converted to a numerical score (d) where the intervals between BG were divided into thirds (**Table I**).

Values of d assigned at rest for both the precordium and subclavian vein sites were used to calculate the Kisman Integrated Severity Score (KISS) according to (16,21):

$$KISS = \frac{100}{4^{\alpha}(t_n - t_1)} \sum_{i=1}^{n} \frac{(t_{i+1} - t_i)(d_{i+1}^{\alpha} + d_i^{\alpha})}{2} \qquad \text{Eq. 1}$$

where t is the time of the observation in minutes after reaching the surface, n is the number of observations (in this case, n = 4), and the power α (chosen to be 3) empirically accounts for the non-linearity of d in the measure of VGE. For subjects that had low VGE on the third observation and were not monitored again, the K-M code for the fourth reading was estimated by assuming that either the frequency or duration component decreased by one unit (depending on which adjustment was deemed most realistic). Essentially, KISS integrates the time distribution of bubble activity recorded during the entire observation period and its value is assumed to be related to the volume of released inert gas. Therefore, KISS is thought to provide a more complete representation of overall bubble activity than the single maximum bubble grade.

Two additional methods of assessing bubble activity were examined, in this case involving values of the K-M code or BG at specific monitoring times. These methods were not used in a previous investigation (15), but herein provide alternate analyses on bubble activity to investigate whether the effects of exercise might be noted in some indices and not in others. In the first method, BG for the precordium at rest and movement were converted to bubble count estimates (BCE in bubbles · cm^{-2}; Table I) using a scale developed by Eftedal et al. (2,9). The BCE scale is based on the number of gas bubbles counted in ultrasonic images of the pulmonary artery in experimental animals and is associated with the bubble grades obtained by using Doppler ultrasound.

In the second method, the K-M code was used to derive a bubble severity estimate (BSE) as an alternate numerical index of bubble activity. The BSE is derived from the following equation:

$$BSE = 0.5 \cdot (a_{min} \times b_{min} \times c^2)^{1/3} + 0.5 \cdot (a_{max} \times b_{max} \times c^2)^{1/3} \qquad \text{Eq. 2}$$

where a_{min} and a_{max} are respectively based on the minimum and maximum number of bubbles per cardiac cycle associated with each value of the frequency parameter, b_{min} and b_{max} are based on the percentage of cardiac cycles with discernable VGE over a 30 s period, and c represents the amplitude parameter (20). Kisman and Masurel derived this numeric 'stress severity' (Kisman KE, Masurel G. Unpublished work; 1978) to rank and group the 64 possible K-M code combinations and generate a BG scale that was compatible with the Spencer system for grading VGE (25). The correspondence between the K-M code, BSE, and BG can be viewed online*. The advantage of the BSE is that it provides a finer distillation of bubble activity than the 12-point BG scale. Table I shows the range of values for BSE that corresponds to BG, d, and BCE. In addition, BSE values can be calculated and analyzed for all observations at both the precordium and subclavian vein sites for both rest and after movement, in contrast to the restrictions of site or condition of VGE monitoring that apply to KISS and BCE. **Table II** summarizes the sites and conditions of measurement applied to each index.

Statistical Analyses

This investigation was originally designed as a three-factorial (type of exercise) times three (time of exercise) study of where (arm, leg, or none) and when (during the dive, during the decompression, or during both) exercise took place. Subjects for these 9 possible combinations were to be assigned entirely at random until there were 12 subjects per cell for a total of 108 individual experimental observations. Several factors including injury, illness, and military and academic obliga-

Supplemental data (Appendix A) are available online at http://www.ingentaselect.com/rpsv/cw/asma/00956562/contpl.htm.

TABLE II. SUMMARY OF INDICES TESTED.

Index	Type	Site	Condition
KISS	summation	P, S	R
BCE	at specific time	P	R, M
BSE	at specific time	P, S	R, M

The type refers to observations over the entire monitoring period (summation) or at specific times (21, 61, 100, and 147 min following decompression). Sites P and S refer to precordium and subclavian veins, and conditions R and M refer to measurements taken at rest and movement, respectively.

TABLE III. MEAN ± SD OF THE SUBJECTS' PHYSICAL CHARACTERISTICS (NUMBER OF SUBJECTS SHOWN IN THE PARENTHESIS).

Variable	A/A (12)	A/I (13)	I/I (13)	I/A (12)	Within (17)
Age (yr)	22.9 ± 4.1	25.8 ± 5.7	29.2 ± 7.8	24.9 ± 4.0	22.8 ± 2.8
Height (cm)	176 ± 3	179 ± 7	179 ± 7	178 ± 7	179 ± 7
Mass (kg)	81.8 ± 10.0	79.4 ± 10.5	80.0 ± 8.9	79.3 ± 10.7	79.6 ± 11.4
Body Fat (%)	24.6 ± 3.5	22.4 ± 4.4	24.3 ± 5.6	22.1 ± 3.6	22.7 ± 5.2
$\dot{V}O_{2max_{arm}}$ ($L \cdot min^{-1}$)	2.10 ± 0.36	2.16 ± 0.53	2.24 ± 0.20	2.16 ± 0.54	2.12 ± 0.48
$\dot{V}O_{2max_{leg}}$ ($L \cdot min^{-1}$)	3.40 ± 0.44	3.40 ± 0.43	3.72 ± 0.51	3.61 ± 0.51	3.53 ± 0.32

The number of subjects for which $\dot{V}O_{2max_{arm}}$ data were obtained are n = 10, 12, 5, 11, and 13 for groups A/A, A/I, I/I, and I/A, and the within-subjects group, respectively. I and A refer to inactivity and activity, respectively, and the order refers to the bottom/decompression phase.

tions reduced the availability of subjects during the allotted time frame and precluded fulfilling the original design.

Preliminary analysis of the VGE data, however, revealed that the effects of arm and leg exercise were not significantly different from each other, whether the exercise was performed during the dive, the decompression, or both. An explanation of this invariance, which was also found in a previous study (15), is given in the discussion. Therefore, the nine trials (according to the type and time of exercise) were collapsed into the following four designations, irrespective of which muscle performed the work: I/I, I/A, A/I, and A/A, where I and A indicate inactivity and activity, and the order refers to the condition during the bottom/decompression phases, respectively. Groups I/I and A/I each contained 13 subjects, and groups A/A and I/A each contained 12 subjects. An unpaired *t*-test (significance at $p < 0.05$) was applied for comparisons of the physical characteristics of the four dive groups.

Subjects who were involved in more than one of the above four dive trial groups were assigned to the dive trial group based on their first dive performed (i.e., if a subject first participated in group I/I and then in group I/A, only the dive in group I/I was selected for the I/I vs. I/A comparison). Thus, all subjects within a particular group were different from those assigned to the comparison group and data were, therefore, treated independently for statistical analyses.

Although numerical in nature, KISS, BCE, and BSE have their origin in the nonparametric K-M codes and BG scale, and were treated as such for analyses. Conceptually, these data can be viewed as a mixed factors design involving activity (I vs. A), site (precordium vs. subclavian, for KISS and BSE), mode (rest vs. movement condition for BCE and BSE), and time (21, 61, 100, and 147 min for BCE and BSE). However, no nonparametric ANOVA is available for multiple factor testing. Further, as the primary concern involves the comparison of bubble activity with or without exercise, a single factor ANOVA, or Mann-Whitney U (or rank sum) test (3) is appropriate for between groups comparisons. Essentially, this test determines whether the observed difference between the median scores of the comparison groups is significant, in this case at $p < 0.05$. This test is considered in some instances to offer a greater power to reject the null hypothesis than the parametric Student's *t*-test.

The Wilcoxon signed rank test (3) was similarly applied for paired comparisons in those cases where sufficient numbers of subjects participated in more than one of the four dive trials (explained further in the results). Subject selection for this test was restricted to those whose dives were a minimum of 7 d apart. Both the rank sum and signed rank tests were particularly suitable for the present data since the test results were invariant to the transformation of the K-M codes, provided that the resultant order of ranking was preserved. For example, while the KISS values would change with a different value of α (Eq. 1), the order of the resultant KISS values would not change.

RESULTS

There were no significant differences in the physical characteristics among the four dive groups (**Table III**). The rates of oxygen consumption during arm work averaged 62.5 ± 11.7% of that observed during leg exercise. This was expected since the $\dot{V}O_{2max_{arm}}$ was similarly proportionally lower than $\dot{V}O_{2max_{leg}}$ (Table III). Yet the VGE data were not sensitive to the type of exercise performed, as remarked on earlier.

The effect of exercise during the bottom phase of a dive on subsequent bubble activity was examined by comparing trials I/I vs. A/I and I/A vs. A/A. No significant differences in any of the bubble activity indices were observed. There were, however, several instances where bubble activity was lower following active decompression whether or not exercise was performed during the bottom phase of the dive (**Table IV**). Thus, all data from those subjects that were inactive during the decompression phase were pooled to form one group (designated I), irrespective of what the subjects did during the bottom phase. Similarly, a second group was formed from those subjects who were active during decompression (designated A). Those subjects who conducted dives in both of these groups (I and A) were selected for the within-subjects comparison (n = 17; Table III). The first dive conducted by these subjects was paired with their first dive performed in the other group. In each case, these dives were separated by at least 7 d. The Wilcoxon signed rank test for paired comparisons revealed that all bubble activity indices were significantly lower following active vs. inactive decompression. For example, **Fig. 2** illustrates the higher frequency of lower BSE scores among active vs. inactive divers.

TABLE IV. INDICATION OF SIGNIFICANT DIFFERENCES BETWEEN DIVES FOR DIFFERENT BUBBLE INDICES.

Index	Site	Time (min)	I/I vs. I/A	A/I vs. A/A
KISS	PR		*	*
	SR			
BCE	PR	21		
		61	*	
		100		
		147		*
	PM	21		
		61	*	
		100	*	*
		147	*	*
BSE	PR	21		
		61		
		100	*	
		147		*
	PM	21		
		61	*	
		100	*	*
		147	*	*
	SR	21		
		61		
		100		
		147		
	SM	21		
		61	*	
		100	*	
		147		

KISS = Kisman Integrated Severity Score; BCE = Bubble Count Estimate; BSE = Bubble Severity Estimate. PR, M = precordium at rest, movement; SR, M = subclavian at rest, movement; and times of measurement are in minutes after surfacing. No differences were found between I/I and A/I, or between I/A and A/A. Significant differences between I/I and I/A, and those between A/I and A/A are indicated by *.

DISCUSSION

The observed VGE activity was not different following arm or leg exercise during decompression even though the energy expenditure during the arm work, calculated from the rate of oxygen consumption ($\dot{V}O_2$), was only 62.5% of the leg work. However, the observed ventilatory equivalent for oxygen was 25% higher during arm exercise ($\dot{V}E/\dot{V}O_2$ = 27.4 L · L_{arm}^{-1} vs. 22.0 L · L_{leg}^{-1}). During decompression, the excess inert gas from supersaturated tissues is eliminated through the simultaneous effects of pulmonary perfusion and alveolar ventilation. Since arm exercise stimulates a greater proportional ventilatory response than leg work (19), moderate arm exercise during decompression may very well be as effective a respiratory stimulant as more vigorous leg exercise for the purpose of enhancing inert gas elimination and reducing the observed VGE. Further, the effects of limb exercise are not exclusive to the exercising limbs. That is, while arm exercise is concentrated in the arms, the accessory musculature of the trunk, hips, and even the legs are recruited to maintain balance and the stability required to crank or lift weights while seated on an underwater ergometer. Thus, the 'muscle pump' of the indirectly involved musculature can markedly increase the venous circulation of tissues far removed from the exercising limbs. This helps to explain the insensitivity of the observed VGE activity with respect to the type of exercise performed.

Contrary to previous reports (4,7,10,28,29), this investigation failed to produce any significant difference in postdive VGE irrespective of the activity status during the bottom phase. This disparity was probably due to differences in the experimental procedures that influenced tissue gas exchange. The increased tissue perfusion induced by the moderate intermittent exercise performed in this study apparently did not enhance the rate of inert gas saturation sufficiently to produce a marked increase in detectable bubble activity after diving. The gas uptake of the "faster" tissues, as might be represented, for example, by tissue compartments of 5- and 10-min half-times without exercise, would be 98.4 and 87.5% saturated after 30 min at depth, respectively, leaving little capacity for further inert gas uptake with exercise. Thus, moderate intermittent exercise during a 30-min dive would not be expected to substantially increase the contribution of these tissues to subsequent bubble formation. On the contrary, inert gas elimination from the faster tissues should be enhanced by exercise during decompression. If these tissues are primarily responsible for the VGE activity after decompression, it

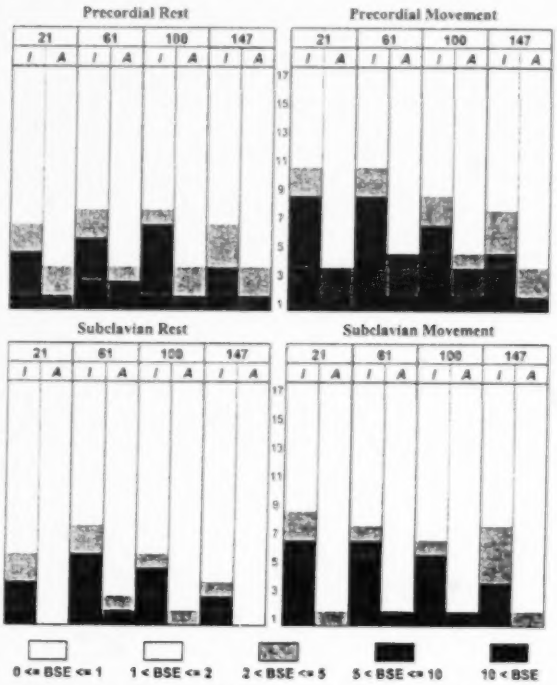

Fig. 2. Occurrence of bubble severity estimates (BSE) within selected ranges for the within-subjects comparison (n = 17) for inactive (I) and active (A) decompression at 21, 61, 100, and 147 min after decompression measured at the precordium and subclavian vein sites at rest and after movement. The mid-vertical column indicates the number of subjects.

seems logical that physical activity during decompression should reduce subsequent bubble activity, as was observed.

The present results are also apparently at variance with the recently published study of Dervay et al. (6), who reported a significant increase in bubble activity in half of the 20 subjects who exercised immediately before altitude decompression. However, that study differed from the present investigation in several important ways. Since the subjects in the Dervay et al. study (6) exercised at ground level, exercising could not have altered the quantity of nitrogen contained within their bodies before decompression. Notably, the exercise performed in the cited study was a fairly strenuous muscular effort (150 deep knee bends within 10 min) that could be expected to provoke the formation of micronuclei immediately before the altitude decompression. In general, however, exercise in astronauts during oxygen prebreathe has been found to be of value provided that strenuous activities are avoided. The subjects in the Dervay et al. study were also inactive during the period of decompression, while in the present study, significant VGE differences occurred only when moderate exercise was performed intermittently throughout the hyperbaric decompression. In addition, the cold water immersion experienced by our subjects likely lowered the perfusion of their superficial tissues, thereby further altering the inert gas exchange between the two studies. Finally, Dervay et al. did not report a control trial (i.e., without exercise) to ascertain whether exercise or decompression per se would have had a different outcome on subsequent bubble activity. Nevertheless, the Dervay et al. study suggests that strenuous exercise performed before the onset of decompression could also significantly increase VGE activity and increase the risk of DCS. The same might also be true of vigorous exercise carried out during the decompression phase of a dive.

The observation of significantly lower KISS, BCE, and BSE values among those subjects that performed separate dives involving exercise and inactivity (Fig. 2) supports the hypothesis that moderate physical activity during decompression decreases VGE activity after diving. This finding also concurs with several previous studies of exercise for divers during decompression and astronauts during oxygen prebreathing provided strenuous muscular effort is avoided (15,17,22,23,28–30). Additionally, the BCE and BSE indices, which use a single "snapshot" observation of bubble activity data, yielded similar findings as the more elaborate KISS, which requires the integration of bubble activity during an entire post-decompression period of observation. This suggests that the simpler BCE and BSE may be appropriate indices of decompression risk, at least under the present study conditions. Whether one index is generally superior to another remains to be determined, perhaps through an investigation involving considerably more and diverse data.

Performing moderate, intermittent exercise during decompression could be a simple, practical, and economical means of reducing VGE and enhancing safety. It is unknown whether continuous rather than intermittent exercise during decompression would yield a further reduction in postdive VGE activity. Strenuous and vigorous exercise was specifically avoided and not investigated during this study because of the increased risk of DCS associated with such exercise. Consequently, unlike the potentially beneficial effects of moderate exercise during decompression, intense physical exercise before, during, and after diving as well as during or after decompression, should still be regarded as potentially dangerous. Yet to be determined is the extent to which an enhanced rate of inert gas elimination and subsequent reduction in VGE due to exercise during decompression may reduce the risk of DCS or the time required for staged decompression.

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